Simulating the Lunar Formation Impact with Smoothed Particle Hydrodynamics

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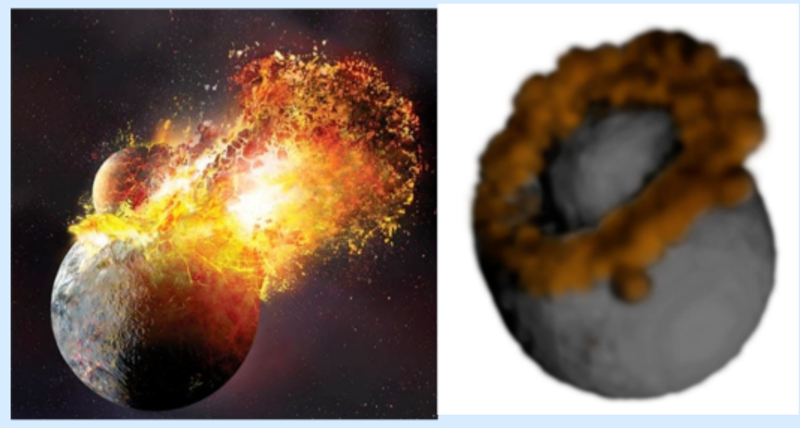
Abstract

The Moon is hypothesized to have been created from a large impact late in the Earth's formation. The currently accepted hypothesis is that a Mars-sized proto-planet catastrophically impacted the proto-earth. The material that was ejected during the collision and traveled fast enough to orbit but not fast enough to escape formed a debris disk orbiting the Earth. The slow-traveling material fell back to Earth and remained, forming an Earth more similar to that of today. This disk then consolidated to form the moon over a timescale of thousands of years.

There are still some remaining questions about the Moon's origin, including why its isotopic signature is so similar to the Earth's despite having formed from a separate body, why the Moon has a small iron core unlike other rocky bodies in the Solar System, and why the Earth-moon system possesses such a large amount of angular momentum. The goal of this project is to answer these questions by simulating the moon formation impact with Spheral, an smoothed particle hydrodynamic (SPH) code developed at LLNL.

Fig. 1: Left: An artist's rendering of the lunar formation event. Right: A single snapshot from the SPH simulation described here.



Methods

The type of simulation used for this project requires a high fidelity hydrodynamics method that preserves total energy and angular momentum, and is not overly diffusive. Thus, the smoothed particle hydrodynamics (SPH) code Spheral, developed here at LLNL, was used. A Lane-Emden type differential solver was employed for a two-component body with an iron core and rocky mantle, under the assumption that the bulk modulus changes very slowly with radius, to solve for the initial states of the proto-Earth and Mars-sized impactor. The LEOS equation of state was utilized to model the iron and basaltic material as well as an RPRPS (Recursive Primitive Refinement Parameterized Spiraling) particle generator to create spherical conformal distributions.

The proto-Earth and impactor consist of 200,000 and 20,000 particles respectively, in order to keep computation costs low and provide accurate simulation results, and each particle was assigned quantities, including mass, velocity, and gravitational potential. The proto-planets were then settled into hydrostatic equilibrium, and collided at various angles.

Analysis

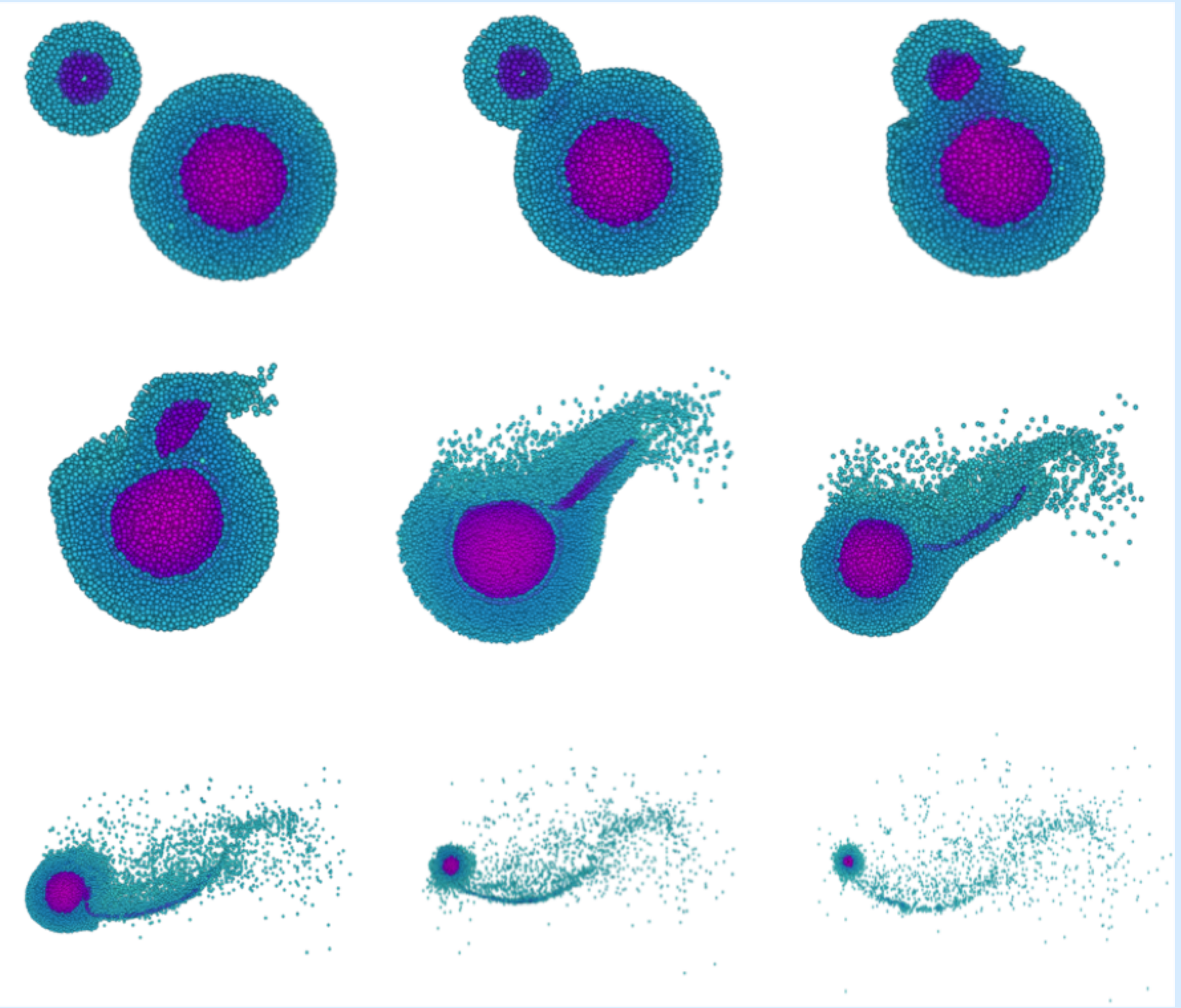


Fig. 2: A simulation of a grazing collision (b=1) of a proto-earth and and a Mars-sized impactor from beginning until 5.5 hours later.

When the collision reaches a steady state as characterized by a debris disk forming in orbit around the Earth, the mass of all material above the Roche limit and below escape velocity is measured to provide an estimate for the resulting Moon's mass. As some of this material may still fall back to Earth, this establishes an upper limit for the mass of the Moon that might form from these disks.

The angular momentum of the system is calculated, as well as the mixing ratio of the material in the disk to determine how much of the material comes from the Earth as opposed to from the impacting body. The impact parameter, mass of the Earth, and mass of the impactor are all then adjusted based on the results of previous collisions to form a more accurate simulation.

References

[1] Cuk, M., and S. T. Stewart. "Making the Moon from a Fast-Spinning Earth: A Giant Impact Followed by Resonant De-spinning." *Science*, vol. 338, no. 6110, 2012, pp. 1047–1052., doi:10.1126/science.1225542.

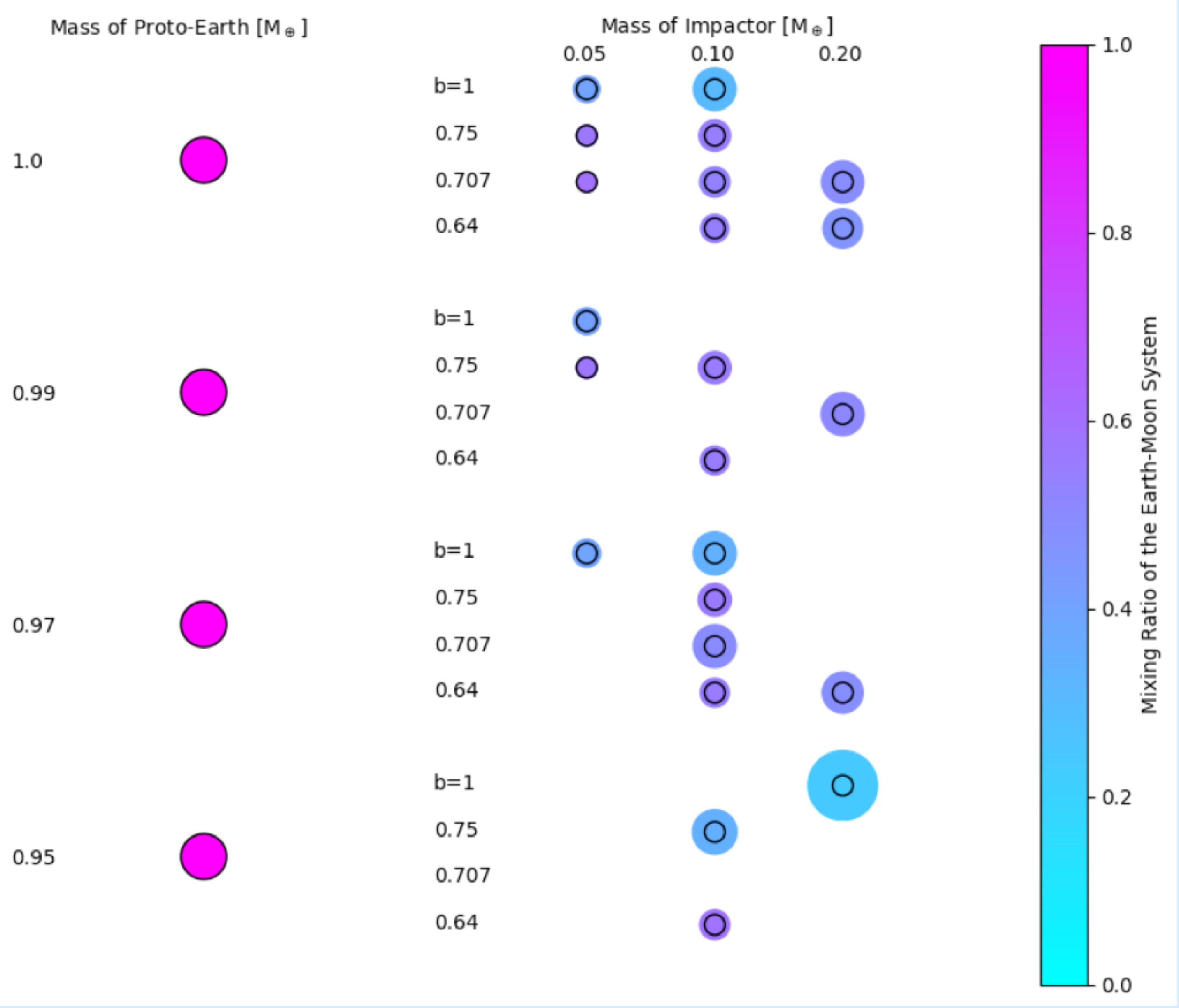
[2]Canup, Robin M. "Simulations of a Late Lunar-Forming Impact." *Icarus*, vol. 168, no. 2, 2004, pp. 433–456., doi:10.1016/j.icarus.2003.09.028.

[3] Canup, R.m., et al. "Lunar-Forming Impacts: High-Resolution SPH and AMR-CTH Simulations." *Icarus*, vol. 222, no. 1, 2013, pp. 200–219., doi:10.1016/j.icarus.2012.10.011.

Thank you to Dr. Cody Raskin for his mentorship.

Results

Fig. 3: The results of various collisions are shown below, with proto-Earth sizes shown on the left, and their corresponding impactor sizes on the right, as well as their impact parameter "b". For reference, an impactor of 0.1 $M_\oplus$ is approximately the size of Mars. The black outline represents the current size of the Moon, and the size of the filled circle corresponds to the mass of the disk. The color describes the mixing ratio of the proto-Earth and impactor material, with 1.0 meaning perfect mixing. The most successful collisions feature a filled circle as large or only slightly larger than the black outline, as that means it formed a disk approximately the size of the moon. The Earth-Moon system today has a mixing ratio of very nearly 1.0, as measured by the oxygen fractionations in rocks returned by the Apollo astronauts.



Conclusion

From these simulations, it appears that the Moon most likely formed from a collision between an impactor slightly smaller than Mars and a proto-Earth of approximately the same mass as the current Earth at an angle of around 50 degrees (b=0.75). The simulations provide similar masses and angular momentum values for the moon today, but the mixing of the impactor and earth material can still be improved upon. Using CRKSPH (Continuously Reproducing Kernel SPH) in Spheral instead of normal SPH is the next step in this research, as that will yield better mixing and a more realistic moon.

Fig. 4: The Moon as it is today

"This work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344."

LLNL-POST-755936